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ORIGINAL PAPER - EXPLORATION GEOLOGY

Diagenesis of unconformity and the influence on reservoir physical properties: a case study of the lower Jurassic in Xiazijie area, Junggar Basin, NW China

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Abstract Diagenesis process of unconformity is very important in understanding the physical properties of the reservoirs. In this paper, based on a comprehensive analysis of well cores, thin sections, casting thin sections, scanning electron microscopy and other data, we discussed the diagenetic characteristics and the influences on reservoir physical properties of unconformity of the lower Jurassic in Xiazijie area, Junggar Basin. The results show that the semi-weathered rock layers of the unconformity had undergone a series of diagenesis, such as compaction, cementation, dissolution and disruption during burial diagenetic evolution. However, the diagenetic evolution is mainly in the stage A of middle diagenesis, and its alteration degree has become gradually weak as the distance increased from the unconformity surface. The quantitative analysis of diagenesis shows that diagenetic characteristics of semi-weathered rock layer of the unconformity are as follows: strong compaction (average optic compaction is 67.28%), middle cementation (average optic cementation rate is 42.97%) and strong dissolution (average optic dissolution porosity is 65.00%). According to their influence on reservoir physical properties, the intensity of diagenesis is sequenced in the following order: compaction > dissolution > cementation > disruption. Among these processes, compaction, dissolution and cementation can change the porosity by −26.1, 6.0 and −4.3%, respectively. Dissolution is the main controlling factor on reservoir properties of unconformity semi-weathered rock layers.

Keywords Unconformity · Semi-weathered rock layer · Diagenesis · Quantitative evaluation · Physical property

Introduction

Reservoir physical properties of sandstones are mainly controlled by tectonism, sedimentation and diagenesis, among which diagenesis determines the ultimate reservoir physical properties (Rodrio and Luiz 2002; Ali et al. 2010; Swei and Tucker 2012). Unconformity represents the transformation at different degrees and types experienced by previous strata from post-geologic functions (Gao and Zha 2008). Post-geologic functions mainly refer to diagenesis such as compaction, cementation, dissolution, packing action and cataclasis. These processes are very common in unconformity and play important roles in determining the physical properties of unconformity and carrier bed, providing effective hydrocarbon migration pathways and reservoir space. In recent years, as the importance of stratigraphic hydrocarbon reservoir exploration is constantly improved, scholars begin to pay attention to unconformity diagenesis and achieve a series of important understanding in diagenesis types and its effect on reservoir physical properties (Purvis 1995; Wei et al. 1998; Miller et al. 2012). However, qualitative research of the unconformity diagenesis is still insufficient due to the unique formation mechanism and complex diagenetic process. Thus, quantitative research has increasingly become the goal of unconformity in fine evaluation.

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The northwestern margin of Junggar Basin is an important block of stratigraphic hydrocarbon reservoir exploration. A number of unconformity-related stratigraphic reservoirs were found in Xiazijie, Urho, Mabei, Xiaoguai and other regions (Wang et al. 2005), from which the oil and gas reserves accounts for 10% of the total reserves, indicating a good exploration prospect of stratigraphic reservoirs. However, major breakthrough still not been made in the clastic stratigraphic reservoir exploration of northwestern margin of Junggar Basin since 2005. Diagenetic characteristics of unconformity and their influence on physical properties, quantitative research of diagenesis are the key limits to stratigraphic hydrocarbon reservoir exploration. In this paper, through outcrop and indoor core observation and analysis of thin sections, casting thin sections, scanning electron microscopy, we take the semi-weathered rock layer of unconformity at lower Jurassic in Xiazijie area of Junggar Basin as an example to discuss the diagenetic characteristics of the unconformable semi-weathered rock layer. In order to deepen the understanding of unconformity and guide fine exploration and development of stratigraphic hydrocarbon reservoirs, we also evaluated the main diagenesis and the impact on physical properties of the carrier bed.

Geological background

Xiazijie area is part of the Xiazijie anticline of the frontal zone of bruchfalten of the Xiahong thrust block. The area is about 21 km^2, facing Xia-1 well field on the east, Xia-18-36 well field on the northwest and Mahu Depression on the south, as shown in Fig. 1. Different formation such as P_3w, T_1b, T_2k, T_3b, J_1b, J_1s, J_2x, J_2t, J_3q and K_1tg are developed from bottom to top in Xiazijie area. The Yanshan tectonic movement in late Triassic not only formed the Xiazijie anticlinal, but also caused erosions on T_3b and T_2k. These strata deposited in the later stage directly upon the Triassic strata, forming the most important regional unconformity between Triassic and Jurassic.

Overlapped traps are developed upon the unconformity surface due to the influence of unconformity and paleotopography. The J_1b stratigraphic overlap oil reservoir is formed in this way. The reservoir is a set of a positive cycle of braided river terrigenous clastic deposit, dominated with channel bar microfacies and channel fill microfacies (Li et al. 2008). It is mainly comprised of conglomerates, sandy conglomerates, pebbled sandstones, etc., with average porosity of over 16% and average permeability of over 50×10^{-3} μm^2; Formation truncation traps are developed beneath the unconformity surface, i.e., the T_2k formation truncation oil reservoir. Fan deltic braided channel and subwater distributary channel are developed in the reservoir (Shang et al. 2007). It is mainly comprised of thick layers of glutenites interbedded by thin layers of pebble sandstones, sandstones, etc., with average porosity of less than 15% (4.78–19.2%) and average permeability of less than 10×10^{-3} μm^2. So far, the proven geological oil reserves and recoverable reserves of the Triassic and Jurassic are 6988×10^4, 208×10^4 and 377×10^4, 82×10^4 t, respectively.

Diagenetic characteristics

The semi-weathered rock layer of unconformity at the lower Jurassic in Xiazijie area is 407.50 m in thickness with buried depth of 1427.50–1835.00 m. It experienced a series of diagenetic evolution. The main diagenesis types are compaction, cementation, dissolution and cataclasis (Fig. 2).

Compaction

Compaction can cause the arrangement of detrital grains from loose to compact, directly resulted in the decreasing of primary pores (Xu et al. 2013). From the casting thin section, we can see that detrital grains in the semi-weathered rock layer are mostly subrounded. Both arenaceous composition and rudaceous composition are comprised of a number of plastic debris grains, such as mudstones, phyllites, schists and micas and semi-plastic debris grains, such as tuffs, rhyolites and andesites. It is usually characterized by low compositional maturity and middle textural maturity. The grain contact relationship is almost all linear as shown in Fig. 2a, b, indicating vital effect of compaction on reservoir property.

Dissolution

Dissolution plays an important role in the construction of unconformity reservoir quality (Wei et al. 1998). It is widely developed in semi-weathered rock layers. The dissolution pore types are mainly intergranular dissolved pores, intragranular dissolved pores and intercrystalline solution pores. Intergranular dissolved pores are primary pores followed by intragranular dissolved pores, while the intercrystalline solution pores are very rare existed. Dissolved substances mainly include feldspar, debris and carbonate cements. Dissolution pores account for a large proportion of pore space and two periods of dissolution can be easily identified. It is deduced that the early dissolution occurred after kaolinisation and before quartz overgrowth while the late dissolution occurred after siderite cementation and many residual primary intergranular pores and dissolution pores are filled and disseminated by later iron clay montmorillonite, as shown in Fig. 2c–f.

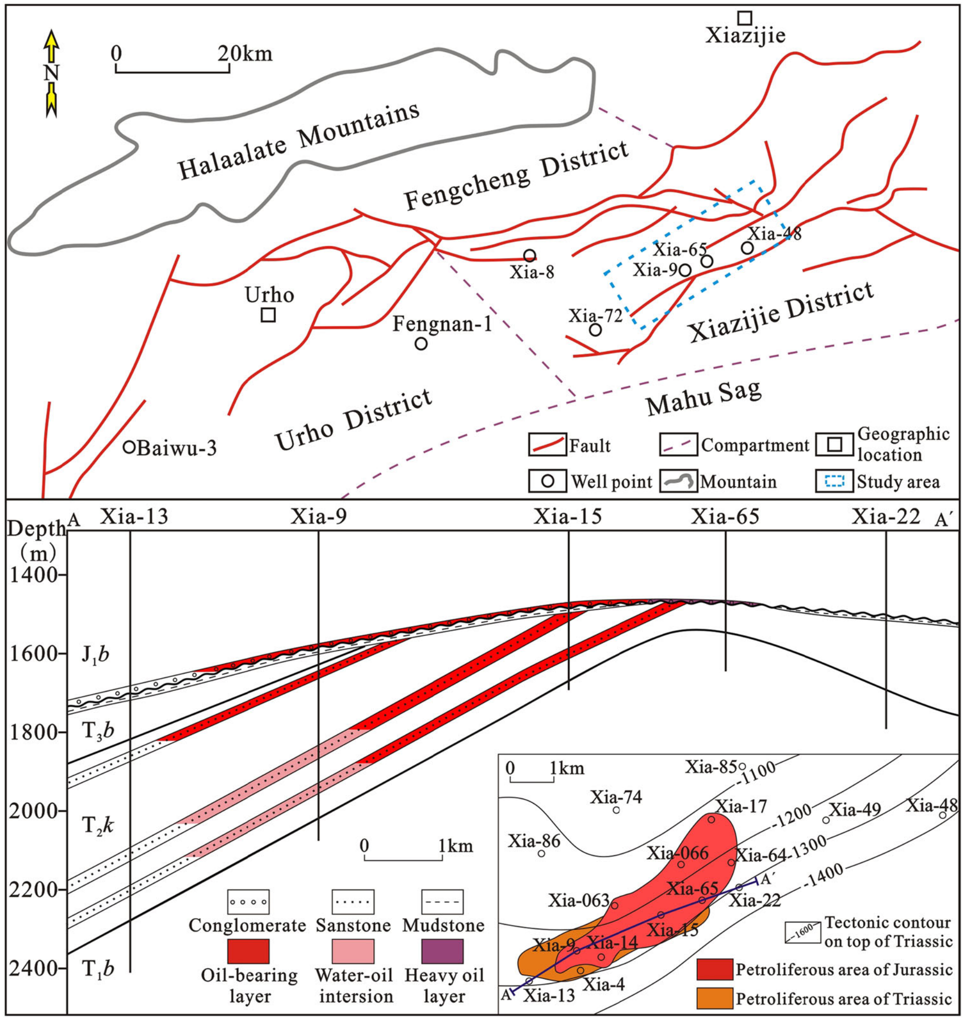


Fig. 1 Location and reservoir profile of Xiazijie area in northwestern margin of Junggar Basin

Cementation

Cementation of semi-weathered rock layers is mainly carbonate cementation and clay mineral cementation followed by siliceous cementation (Fig. 2g–j). The carbonate cementation characteristic is special: siderite cementation is widespread (content is 33.9%) and distributed in the form of pelletoid or powder crystal between grains and often associated with biotite. Calcite cementation is very few (content is 8.7%) and no ferrocalcite, dolomite and ankerite cementation are found. According to the high content of siderite and low content of calcite, it can be concluded that there should be two periods of carbonate cementations. The calcite cementation occurs earlier than the siderite cementation. Clay minerals mainly include kaolinite and illite/smectite mixed layers, illite, kaolinite and chlorite. The disappearance of smectite is an important diagenetic indicator of the semi-weathered rock layer, showing the middle diagenetic phase. Dehydration of smectite leads to its transformation into illite. The content of illite/smectite mixed layer and illite is relatively high (19–69%) whereas content of kaolinite is the highest (28–81%) and the content of illite is low (0–10%), all of which are decreased as the buried depth increased. The siliceous cementation is mainly in the form of quartz overgrowth (Well Xia-64, 1479.15 m; Well Xia-48, 1529.00 m) with a content of generally lower than 3%. A certain relationship is apparently existed between the degree of quartz overgrowth and buried depth. The degree of quartz overgrowth increases with the depth of unconformity decreases.

Cataclasis

The pressure from the overlying formation increases with the buried depth increases, resulting in compressional rupture between mineral particles and microfracture development. Microfractures are not only conducive to acidic fluid migration and dissolution, but also can discharge the high concentration flow after the dissolution,

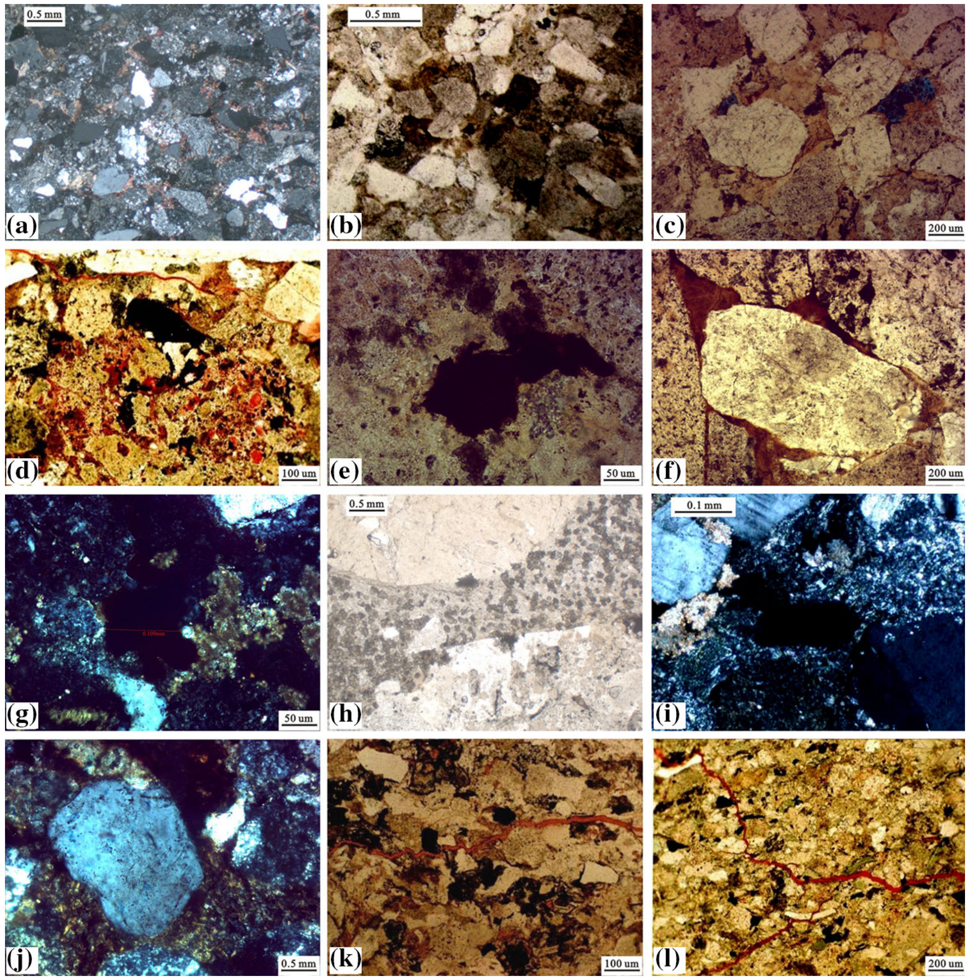


Fig. 2 Diagenetic characteristics of the semi-weathered rock layer of unconformity. **a** Well Xia-48, 1 529.00 m, particle line contact, plane polarized light. **b** Well Xia-48, 1 538.50 m, particle line contact, plane light. **c** Well Xia-64, 1 480.15 m, intragranular dissolved pore, plane light. **d** Well Xia-65, 1 483.00 m, intergranular dissolved pore, 5 × 10. **e** Well Xia-64, 1 480.15 m, iron clay montmorillonite fill dissolved pore, plane light. **f** Well Xia-65, 1 483.00 m, residual iron clay montmorillonite fill intergranular pore, plane light. **g** Well Xia-64, 1 480.15 m, siderite cementation, plane polarized light. **h** Well Xia-15, 1 539.44 m, siderite in the form of pelletoid, plain light. **i** Well Xia-48, 1 529 m, argillaceous and calcite cementation, plane polarized light. **j** Well Xia-64, 1 479.15 m, quartz overgrowth, plane polarized light. **k** Well Xia-64, 1 478.65 m, microfracture, 8 × 10, cast; **l** Well Xia-65, 1 560.13 m, microfracture, 6.3 × 10, cast

resulting in the strengthened dissolution (Liao 2013). Microfractures are relatively developed in the semi-weathered rock layer, which can connect residual primary pores with secondary pores and consequently improve the flowing property of the semi-weathered rock layer (Fig. 2k, l).

Diagenetic evolutionary sequence and diagenetic stage

Based on microscopic observation, the main diagenetic evolutionary sequence of the semi-weathered rock layer is: particle argillation, compaction → chloritization, illitization → calcilization → kaolinisation → dissolution → quartz overgrowth → sideritization → dissolution → iron clay montmorillonite filling. According to the internal data from the Xinjiang Oilfield, the maximum pyrolysis temperature (T_{max}) of Well X74 is about 430–435 °C from 1000 to 1500 m, and Ro of Well X34 is about 0.5–0.7% from 1000 to 2100 m. Based on the comprehensive analysis of Ro, T_{max}, illite/smectite mixed layer ratio, other sensitive parameters of diagenetic evolution stages and the pore types, characteristics of clay minerals, the diagenetic evolution stage is divided into stage A and stage B in early diagenesis and A subage is combined with middle diagenesis. Currently, the reservoir is wholly experiencing A subage of middle diagenesis. In summary, main diagenetic features of the semi-weathered rock layer of unconformity at lower Jurassic in Xiazijie area are: the grain contact relationship is almost linear, compaction is relatively strong, cementation is mainly siderite cementation and shale matrix filling, dissolution pores and microfractures are well developed, rock alteration is regularly widespread and characterized by the intensity of alteration weakening with the increased depth of unconformity (Fig. 3).

Diagenesis evaluation

After analyzing the sample data of 14 cores from three wells in Xiazijie area and the statistics of particle features of rocks, pore composition and matrix composition, we calculated the parameters such as apparent compaction percentage, apparent cementation rate and apparently

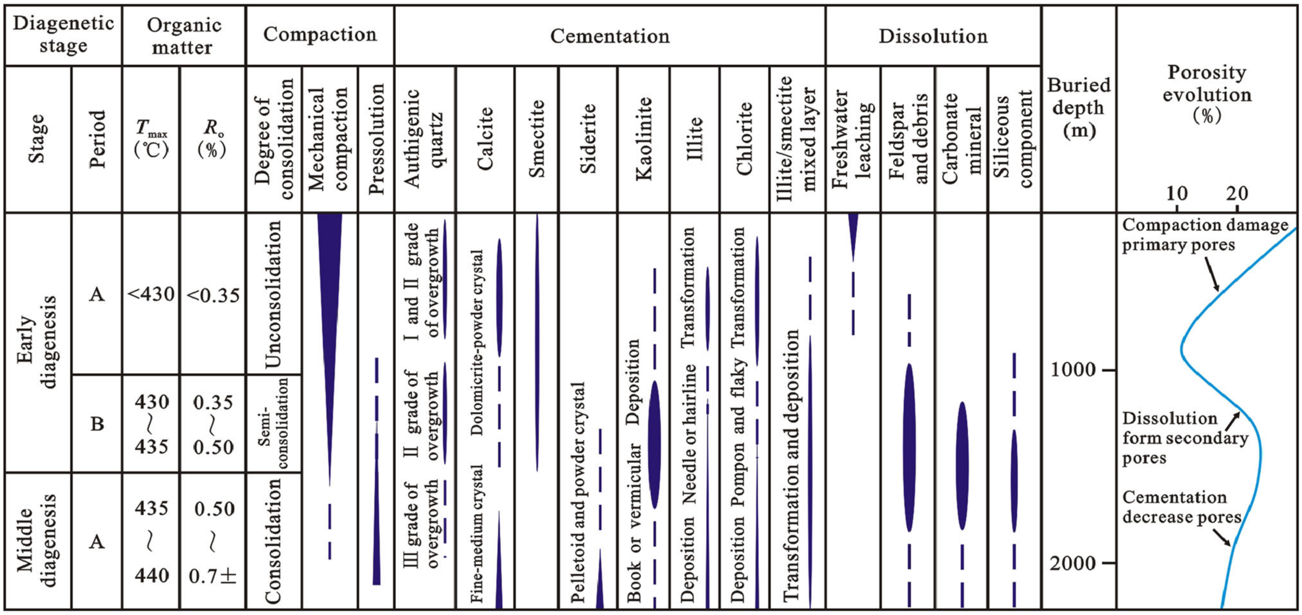


Fig. 3 Division of diagenetic stages of the semi-weathered rock layer of unconformity

relative dissolution porosity of the semi-weathered rock layer of unconformity of upper Triassic. The average value are 67.28, 42.97 and 65.00%, respectively, as shown in Tables 1 and 2. The apparent compaction percentage refers to the ratio between loosed porosity by compaction and primary porosity. The value of apparent cementation rate is based on total cementing to residual porosity between grains after compaction. The apparently relative dissolution porosity is the ratio of dissolution porosity to primary porosity. We can find significant impaction of compaction, cementation and dissolution on reservoir physical property of the semi-weathered rock layer of unconformity, which indicate that the diagenesis is very complicated.

Discussion

Effect of diagenesis on physical property of unconformity reservoir can be discussed through analysis of features of diagenesis and intensity evaluation of diagenesis of the semi-weathered rock layer.

Effect of compaction on reservoir physical property

Although weak correlation exists between burial depth and apparent compaction percentage and samples with similar apparent compaction percentage display wide variation in burial depth, it seems that compaction of the semi-weathered rock layer increases with the burial depth increases. Meanwhile, porosity decreases linearly with compaction (Fig. 4). The reservoir porosity is decreased by 26.1% because of compaction indicates its important in physical property of the semi-weathered rock layer. The controlling action is mainly affected by buried depth, clastic particle features and the content of plastic and semi-plastic detrital grains plastic in the semi-weathered rock layer, which is relatively high. The rigid detrital grains account for 38%, semi-plastic detrital grains account for 37% and plastic detrital grains account for 25%. The detrital grains experience flexible deformation and then are partly squeezed in intergranular pores as the overlying formation pressure enhances, resulting in damage to the primary pores.

Effect of cementation on reservoir physical property

As mentioned above, siderite, which blocks a lot of pore spaces, is widespread in the semi-weathered rock layer as pelletoid or crystal powder cemented between grains, resulting 4.3% loss of reservoir porosity. The evaluation results show that porosity decreases as the intensity of cementation increases (Fig. 5 left). In addition, cementation mainly reduces porosity of the semi-weathered rock layer rather than support particles to preserve primary pores.

Effect of dissolution on reservoir physical property

Secondary pores of the semi-weathered rock layer are mainly formed because of the dissolution. Porosity of the

Table 1 Quantitative evaluation parameters of diagenesis of the semi-weathered rock layer of unconformity

Sample depth/m	Content of cement/%	Surface porosity/%	Dissolution surface porosity/%	Apparent compaction percentage/%	Apparent cementation rate/%	Apparent dissolution ability/%	Data sources
1478.65	11.00	28.00	18.76	49.40	54.35	23.52	Well Xia-64
1479.60	5.00	20.00	14.20	73.00	46.30	15.92	Well Xia-64
1481.73	7.00	20.00	8.40	53.50	37.63	10.32	Well Xia-64
1488.72	3.00	13.00	6.63	76.58	32.02	7.32	Well Xia-65
1490.70	8.00	16.00	6.88	57.20	46.73	8.30	Well Xia-65
1522.22	2.00	13.00	10.40	88.50	43.48	10.90	Well Xia-063
1523.62	2.00	15.00	6.90	74.75	19.80	7.68	Well Xia-65
1524.16	5.00	16.00	8.80	69.50	40.98	10.02	Well Xia-063
1526.43	9.00	17.00	9.01	57.53	52.97	10.85	Well Xia-65
1527.65	1.00	15.00	7.05	77.63	11.17	7.74	Well Xia-65
1527.81	16.00	1.00	0.34	58.35	96.04	0.41	Well Xia-65
1529.67	5.00	6.00	2.10	77.75	56.18	2.31	Well Xia-063
1561.03	8.00	15.00	5.85	57.13	46.65	7.06	Well Xia-65
1562.33	2.00	18.00	8.46	71.15	17.33	9.56	Well Xia-65

Table 2 Intensity evaluation results of diagenesis of the semi-weathered rock layer of unconformity

Apparent compaction percentage/%		Apparent cementation rate/%		Apparent relative dissolution porosity/%	
Average value	67.28	Average value	42.97	Average value	65.00
Strength	Strong	Strength	Medium	Strength	Strong

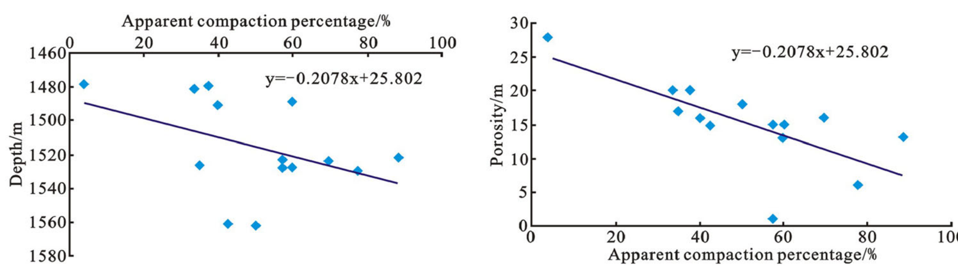


Fig. 4 Diagram of compaction and depth and porosity of the semi-weathered rock layer of unconformity

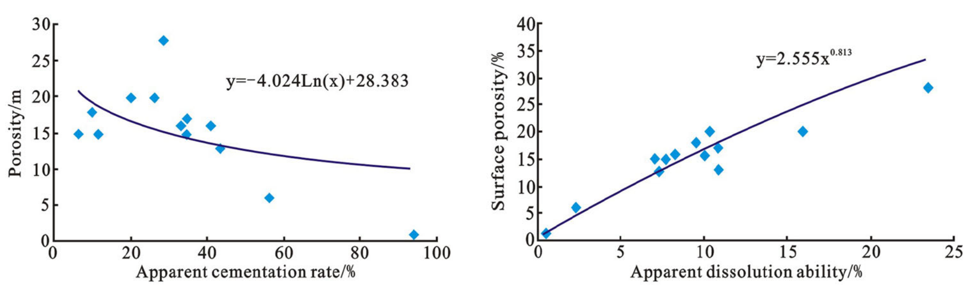


Fig. 5 Relationship between cementation (*left*), dissolution (*right*) and porosity of the semi-weathered rock layer

semi-weathered rock layer increases as the dissolution intensity enhances (Fig. 5 right). Thus, dissolution is not only important in increasing pores but also is an indirect reflection of the prime role of the produced pores by dissolution. It can also be revealed in Fig. 6 that the content of dissolution pores in different wells at different depth is relatively high (average 51%), which indicates that dissolution is the major diagenesis in increasing the pore space (6.0%).

Effect of cataclasis on reservoir physical property

A small amount of microfractures are found in semi-weathered rock layer (Fig. 2k, l). Most of the

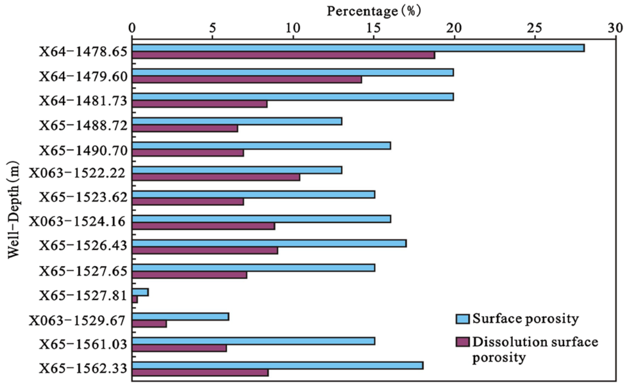


Fig. 6 Diagram of surface porosity and dissolution surface porosity of the semi-weathered rock layer

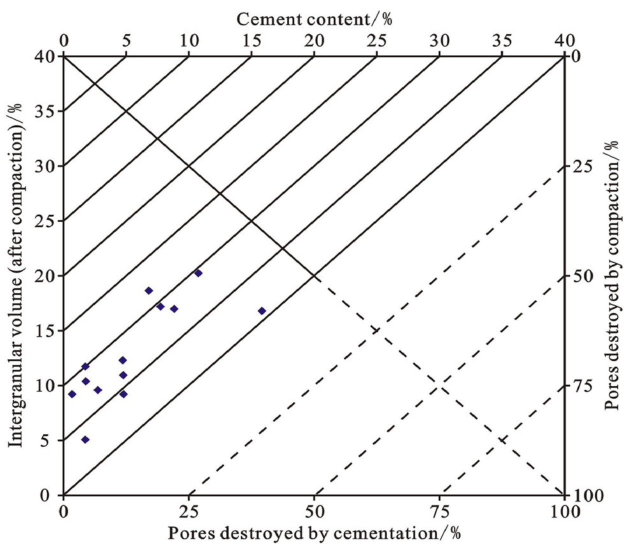


Fig. 7 Evaluation map of relative intensity of compaction and cementation of the semi-weathered rock layer

microfractures are suffered from weathering–leaching alteration to form dissolution microfractures, which contribute to the increase of the flow capacity of the semi-weathered rock layer.

Comparison of diagenetic intensity

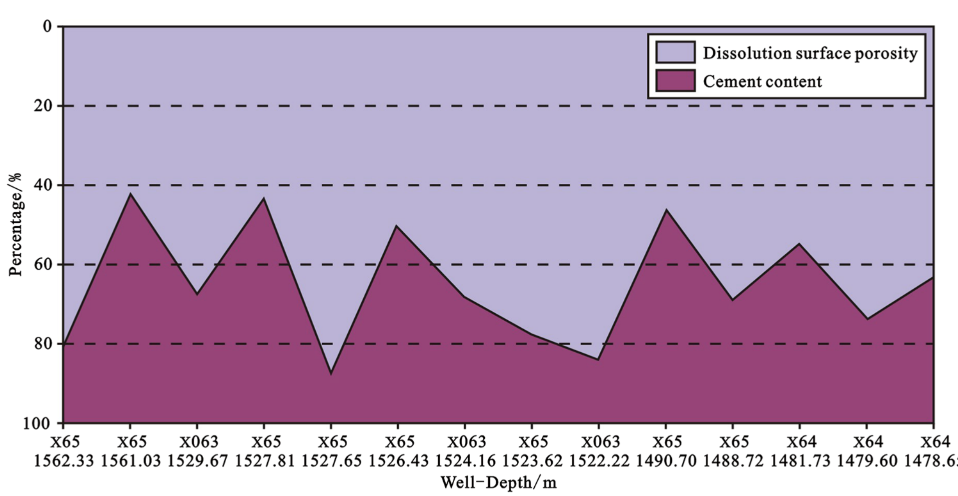
Compaction and cementation are main diagenesis types in reducing the reservoir porosity. Their influence on porosity can be evaluated through porosity reduction caused by compaction and cementation. As shown in Fig. 7, all the data are at the left-bottom of the diagonal line, indicating porosity reduction by compaction exceeds that by cementation. Compaction is the chief diagenesis that results in poor reservoir physical properties.

Cementation and dissolution are measured by the content of cement and apparent dissolution surface porosity, respectively. Relative intensity of cementation and dissolution is characterized by the content of cement/apparent dissolution surface porosity ratio. As shown in Fig. 8, dissolution has a significant influence on the formation of pores in the semi-weathered rock layer.

Conclusion

The semi-weathered rock layer of the unconformity at lower Jurassic in Xiazijie area is undergone a series of diagenesis during the formation process, such as compaction, cementation and dissolution. The unconformity reservoir is mainly remained in the stage A of middle diagenesis, which alteration intensity has become gradually weak along with the increase of distance from unconformity surface. The quantitative evaluation of diagenesis shows that the semi-weathered rock layer has diagenetic

Fig. 8 Evaluation map of relative intensity of dissolution and cementation of the semi-weathered rock layer



characteristics as follows: strong compaction, middle cementation and strong dissolution. The relatively intensity of diagenesis are arranged according to their influence on reservoir physical property in the following order: compaction > dissolution > cementation > disruption. Compaction, cementation and dissolution can cause −26.1, −4.3 and 6.0% of porosity fluctuations, respectively, and dissolution is important constructive diagenesis.

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